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ABSTRACT

Because of the recent national concern over the future availability of energy supplies, the federal government has initiated a program to investigate alternative energy sources. Among the alternatives under consideration is the utilization of wind energy. A major phase of the wind energy program is the development of reliable wind turbines for supplying cost-competitive electrical energy. This paper discusses the preliminary results of two projects in this phase of the program. First an experimental 100 kW wind turbine design and its status are reviewed. Also discussed are the results of two parallel design studies for determining the configurations and power levels for wind turbines with minimum energy costs. These studies show wind energy costs of 7 to 1.5 ¢/kWH for wind turbines produced in quantities of 100 to 1000 a year and located at sites having average winds of 12 to 18 mph.

INTRODUCTION

Man has used the wind for years as a source of energy for many of his applications. These applications have included sailing ships for transportation and wind turbines for supplying mechanical power. The wind turbine applications have included the pumping of water, grinding of grain and more recently the generation of electricity.

Because of the recent national concern over the dwindling supplies of domestic gas and oil, the federal government has initiated a program to investigate alternative energy sources including wind energy. The recently formed Energy Research and Development Administration (ERDA) has been assigned the responsibility for managing these energy programs.

Agreement has been reached that, under the overall program management of ERDA, the NASA-Lewis Research Center will provide project management for the large experimental wind turbine phase and the associated supporting research and technology phase of the wind energy program. A recent report "Plans and Status of the NASA-Lewis Research Center Wind Energy Project" describes briefly the major large wind turbine projects that are underway.[1] These projects include a 100 kW experimental wind turbine, the first industry-built and user-

operated wind turbines, the supporting research and technology, follow-on improved wind turbines, and 10 MW to 100 MW interconnected systems of wind turbines.

This paper briefly discusses the design and status of the 100 kW experimental wind turbine and preliminary results obtained from design studies performed by industry. This latter design phase is primarily concerned with identifying the configuration and size of horizontal-axis propeller-type wind turbines that will result in delivering the lowest cost energy for a given mean wind speed.

100 kW EXPERIMENTAL WIND TURBINE

The 100 kW experimental wind turbine project has been described in three previously published reports.[1,2,3] This wind turbine is very near completion and is scheduled to begin operation in late summer at the NASA Plum Brook site near Sandusky, Ohio.

In summary, this horizontal-axis, propeller type wind turbine has a two-bladed 125-foot diameter rotor driving a 100 kW synchronous alternator through a step-up gear box. The rotor is located downwind of the tower and rotates at a constant speed of 40 rpm. The alternator operates at 1800 rpm and delivers 60 hz three-phase power. Figure 1 shows a sketch of the overall 100 kW wind turbine with the details of the 100 kW drive train assembly and yaw system shown in figure 2. The wind-turbine rotor starts up at a wind speed of 9 mph and begins to deliver power at 9.5 mph. Figure 3 shows the variation of power output of the wind turbine as a function of wind velocity. Also shown in figure 3 is a corresponding plot of rotor blade angle as a function of wind velocity. Figure 4 is a plot of the calculated coefficient of power, C_p, versus tip speed ratio, λ, for the 100 kW wind turbine. The coefficient of power, C_p, is defined as the power output of the rotor divided by the theoretical power in the area of the rotor disc for the undisturbed upstream wind velocity. The tip speed ratio, λ, is defined as the ratio of the rotor tip velocity divided by the undisturbed upstream wind velocity. At 18 mph the 100 kW wind turbine operates at a λ of 10 and has a C_p of 0.375.

The blades for the wind turbine were built by the Lockheed Company of Burbank, California, and a report of their design and fabrication has been written.[4] Figure 5 shows the blades being delivered to the hangar at the Lewis Research Center where they were inspected and matched to the wind turbine hub.

The power train excluding the yaw system, hub and blades was assembled and tested for 50 hours at various load levels at the Lewis Research Center prior to shipment to the Plumbrook Site. Figure 6 shows the power train under test in a test cell at Lewis.

At the present time the wind turbine has been installed at the base of the tower at the Plum Brook site for final assembly and testing prior to installation on top the tower, (fig. 7).

Testing of the 100 kW wind turbine will initially consist of checking loadings of blades and shafts at various wind speeds and checkout of all controls. These tests will be attended (operators continuously on duty in the Control Room) and the alternator power will be dissipated in a resistive load. Tests will eventually become unattended (no operators on duty) and include operating the wind turbine in parallel with a diesel-generator. In later tests the wind turbine will be connected to a local utility grid.

In addition to the system tests, it is planned to use the 100 kW wind turbine for testing other wind turbine components such as: composite rotor blades, induction generators, rolling traction transmissions and rotor hubs that can pivot slightly out of the plane of rotation (teetered hubs). These alternate components will result primarily from the supporting research and technology efforts and should lead to lower cost more reliable wind turbine designs.

FIRST GENERATION INDUSTRY-BUILT USER-OPERATED WIND TURBINES

The objective of this phase of the wind energy project is to involve industry and users in the design and implementation of optimized wind turbines that are capable of supplying electrical power at costs competitive with conventional power sources. Also during the course of this effort, attention will be paid to evaluating the public reaction and/or acceptance of large wind turbines. To meet these objectives the following multi-phased project has been initiated:

(1) Design study contracts
(2) Evaluation of designs and competitive contract preparation
(3) Detail design, fabrication, assembly and operation contracts
(4) Operation and reporting of performance of experimental wind turbines.

The objectives and plans for these phases of the wind energy program have been fully described in reference 1. This report will concentrate on the results of efforts to date and a brief discussion of the follow-on plans.

Design Study Contracts

Two parallel 9 month study contracts were awarded in mid-November 1974 for the selection and design of minimum energy cost wind turbines. These contracts, at a cost of approximately $500,000 each were awarded to the General Electric Company and the Kaman Aerospace Corporation. The contract scope was limited to the study of horizontal-axis, propeller type wind turbines that could produce electric power acceptable for utility grids. The effort encompassed four major tasks (fig. 8) which included conceptual design; parametric analysis; preliminary design and definition of utility interface requirements.

The contractors evaluated a number of candidate configurations for wind turbines. Figure 9 summarizes the various configurations evaluated. After initial cost studies, both contractors independently concluded that for minimum energy cost the wind turbine should have a variable-pitch constant-speed two-bladed rotor operating downwind of the tower. The rotor should drive a synchronous or induction alternator through a conventional step-up gearbox. The early results of these studies obtained by Kaman were summarized by Meier in a

paper presented at the American Helicopter Society in May 1975.[5]

During the parametric and optimization task, capital and energy costs were determined for a range of wind turbines optimized for minimum energy cost (¢/kWH). The wind turbines analyzed range from 50 kW to 3000 kW. NASA furnished wind velocity duration curves, (fig. 10), were used for all energy calculations in the design studies. It was assumed that the wind velocity is defined at an elevation of 30 ft.

The results of the parametric and optimization task for the two contracts are shown in figure 11 for energy costs (¢/kWH) as a function of mean wind speed and rated wind turbine power. For comparison purposes, generation cost for power in the U.S. today generally falls in the 0.1 to 5¢/kWH range. These curves indicate that wind turbines could be competitive today with some existing power generation systems.

The initial costs obtained by both contractors differed by a factor of nearly three, but the trends were in agreement. Both showed that minimum energy cost designs existed at each mean wind speed and that those minimum energy cost designs increased in power rating with increased mean wind speed. Also both studies showed that at each mean wind speed energy costs were high for the lower power wind turbines while for wind turbines up to 3000 kW the cost remained low and near the lowest energy cost design for that mean wind speed.

Note that the curves shown in figure 11 represent a wind turbine optimized for lowest energy cost for that specific mean wind speed.

In addition to minimum energy cost there is also the question of the wind turbine plant factor. Plant factor (PF) is defined as the ratio of the energy the wind turbine will deliver over a year for mean wind speed to the amount of energy it would generate in a year if it operated at rated power continuously.

$$PF = \frac{\text{Generated Annual-kWH}}{\text{Rated kW} \times 8760\ \text{Hr}}$$

Plant factor gives an indication of how effectively a wind turbine is being utilized. High plant factor wind turbines generally have large rotors in comparison to their rated power output or alternator size and thereby operate more hours at rated output. However, wind turbines with high plant factors will not necessarily generate the lowest cost energy. High PF wind turbines generally capture more energy but are also more expensive to build because of the larger rotors.

The selection of a minimum energy cost wind turbine versus a wind turbine with a higher PF is definitely an issue that depends on how the wind turbine is to be used. If the application can use bulk energy whenever it is available, then the minimum energy cost design is preferred. If energy storage is needed, then the higher plant factor wind turbine probably will result in

the best overall systems choice. This option is clearly dependent on the resultant user's application.

Before selecting the wind turbine, sizes and the mean wind speeds for preliminary design, the following question was addressed: How sensitive to mean wind speed is an optimized design? That is, given an optimized design of, say, 1500 kW for an 18 mph site, what is the effect on energy costs of putting this design on sites with a mean wind speed of 15 mph or 21 mph. Studies were conducted by both contractors to answer this question. The results of these studies for a 500 kW wind turbine, 12 mph mean wind speed site and a 1500 kW wind turbine, 18 mph mean wind speed site are plotted in figure 12.

Significantly, the results show that for less than 10 percent increase in energy costs the wind turbine designed for 500 kW at 12 mph can be used at sites with 9 to 15 mph and the 1500 kW design can be used at sites with 15 to 21 mph wind. Thus it appears that the two designs could be used for a relatively wide range of sites with only a small penalty in energy cost.

From the results of the parametric study and optimization tasks, two designs were selected for further definition during the preliminary design task; 500 kW at 12 mph and 1500 kW at 18 mph. The conceptual, and parametric analysis studies were performed to obtain the minimum energy cost wind turbine designs. However, in the final selection attention was paid to plant factor and the designs selected were slightly off optimum to take advantage of higher plant factors at increases in energy cost of only a few percent. The capital cost of these higher plant factor wind turbines is greater but because more energy is generated, the resulting energy costs are nearly those of the minimum energy-cost design.

At this time most of the preliminary design has been completed and Table 1 summarizes the results to date of both contractor efforts for these two designs.

In addition to determining the optimum designs, a major part of the design study efforts was to determine the interface requirements for connecting wind turbines to typical utility grids. These interface requirements included items such as required electrical interface switchgear, automatic protection and controls and required operation and maintenance procedures. Figure 13 summarizes the interface requirements. Figure 14 identifies some of the operational and institutional issues considered. These studies show no interface or institutional problems that pose major barriers to the installation of wind turbines on utility grids.

This presentation does not try to summarize all the results of the four design study tasks but has only discussed the major results. The two final contractor reports will contain all the information determined from the two parallel design studies.

Plans for Follow-On Efforts

Following the completion of the design studies, a competitive request for procurement (RFP) will be issued for the detail design, fabrication, assembly and operation of a 1500 kW wind turbine. The specifications for the 1500 kW wind turbine will be determined after an evaluation of the results of the two design studies have been completed. We hope to have the contract for the 1500 kW wind turbine signed in early 1976 so that operation can be initiated by the end of 1977 on a selected user's site.

In addition to the 1500 kW wind turbine, it is now planned to initiate a contract effort for several optimized 500 kW wind turbines following the 1500 kW procurement. Also, since the 100 kW experimental wind turbine is similar to the resulting optimized concepts, we plan to install one or two 100 to 200 kW versions of this design on selected user sites. These machines could be fabricated and installed on selected sites by the end of 1976 or early 1977. Installation of these machines would provide earlier information on working with users, such as utilities, that will be helpful in implementing the follow-on 1500 kW and 500 kW wind turbines as soon as possible. A summary schedule for the above planned efforts is shown in figure 15.

CONCLUDING REMARKS

The preliminary results from the large experimental wind turbine phase of the national wind energy program have been summarized in this paper.

The 100 experimental wind turbine is in the final stages of assembly and is planned to begin operation late this summer. This wind turbine will provide early performance and operation data for the wind energy program. In addition it will serve as a test bed for evaluating improved and/or lower-cost components and systems.

The two parallel study contracts for the design of large wind turbines with minimum energy costs are nearly complete. Both contracts have reached the following general conclusions:

(1) For minimum energy cost the wind turbine should have a variable-pitch constant-speed two-bladed rotor operating downwind of the tower. The rotor should drive a synchronous or induction alternator through a conventional step up gear box.

(2) Both contracts have shown that optimum size machines (minimum energy costs) exist for each mean wind speed. These results show that the power rating for these optimized machines increases with increased mean wind speed: for an 18 mph site the power rating is approximately 1500 kW while it is closer to 500 kW at a 12 mph mean wind site. The 1500 kW and 500 kW wind turbines at 18 mph and 12 mph mean wind sites have been selected for preliminary design.

(3) Estimated energy cost for wind turbines is 3 to 7 ¢/kWH for sites with 12 mph mean wind speed and 1.5 to 3 ¢/kWH for sites with 18 mph mean wind speeds. These costs compare favorably with some conventional power generation systems. These estimates are based on assummed production rates of 100 to 1000 wind turbines per year.

(4) Additional studies have shown that the two selected designs can be used on sites with higher or lower mean wind speeds with a small penalty in increased energy costs. For example, the 1500 kW wind turbine can be placed in a 15 mph or 21 mph mean wind site with less than 10 percent increase in energy cost over a wind turbine optimized for 15 mph or 18 mph. This result indicates that only a few wind turbine designs will be needed to meet the range of sites with useful mean wind speeds.

(5) The design study contractors have also shown that wind turbine designs with reasonably higher plant factors can be selected with very small increases in energy costs. The question of high or low PF wind turbines is very application related and dependent on whether energy storage is needed with the wind turbine.

(6) The design studies indicate that no apparent major institutional or interface requirements have been discovered that could provide a major barrier to the implementation of wind turbines on utility power grids.

In summary, the results of the large wind turbine project indicate that wind turbines of 500 kW to 1500 kW and larger appear to offer the potential for delivering electrical energy at costs that are competitive with some conventional power generation systems. These results are dependent on obtaining suitable sites that have nominal mean wind speeds of 12 mph for a 500 kW power level and 18 mph for a 1500 kW power level.

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2. R. L. Puthoff and P. J. Sirocky: Preliminary Design of a 100 kW Wind Turbine Generator, NASA TM X-71585, 1974.

3. R. L. Puthoff and P. J. Sirocky: Status Report of 100 kW Experimental Wind Turbine Generator Project, NASA TM X-71758.

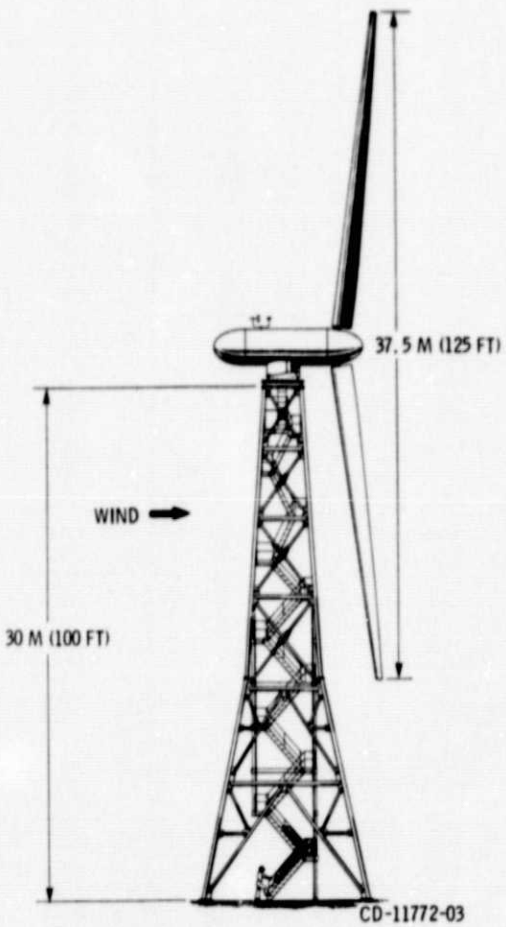
4. R. E. Donham, J. Schmidt, B. S. Linscott: 100 kW Hingeless Metal Wind Turbine Blade Design, Analysis and Fabrication. Presented at the 31st Annual National Forum of the American Helicopter Society, Washington, D.C., May 1975. Preprint No. S-998.

5. R. C. Meier: Concept Selection and Analysis of Large Wind Generator Systems. Presented at the 31st Annual National Forum of the American Helicopter Society, Washington, D.C., May 1975.

TABLE I. - RESULTS OF PRELIMINARY DESIGN TASK FOR LOW AND HIGH

POWER WIND TURBINES

	Low Power		High Power	
	GE	Kaman	GE	Kaman
Mean Wind Speed	12	12	18	18
Rated Power, kW	500	500	1500	1500
Rated Wind Speed, mph	16.3	20.5	22.5	25
Rotor Diameter, ft	183	150	190	180
Rotor Solidity		3%		3%
Rotor Speed, rpm	29	32.3	40	34.4
Energy Cost, ¢/kWH	4.18	5.55	1.65	2.02
Capital Cost, $/kW	974	901	449	481
Wind Turbine Cost, $	486,000	450,670	674,000	720,800
Plant Factor	0.42	0.29	0.51	0.43



Firure 1. - 100-kilowatt experimental wind turbine.

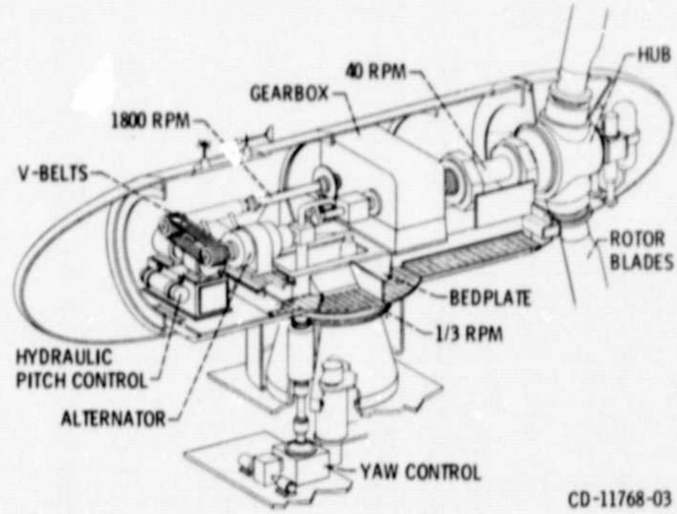


Figure 2. - 100-kilowatt wind turbine drive train assembly and yaw system.

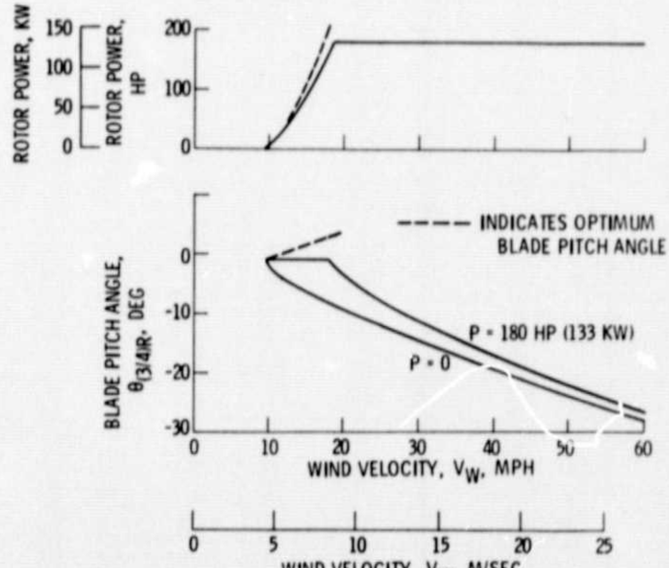


Figure 3. - Rotor power and blade angle variation for the 100-kilowatt experimental wind turbine.

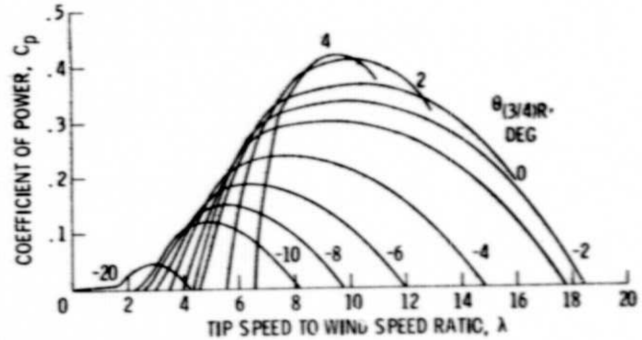


Figure 4. - Coefficient of power for 100-kilowatt experimental wind turbine.

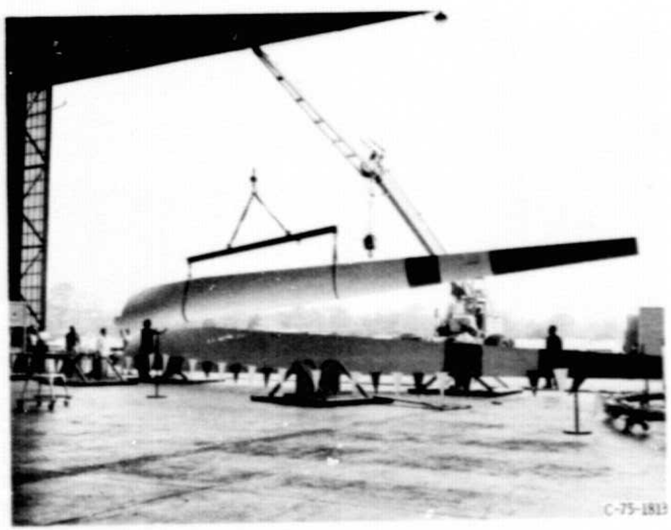


Figure 5. - Unloading a 100 KW wind turbine blade.

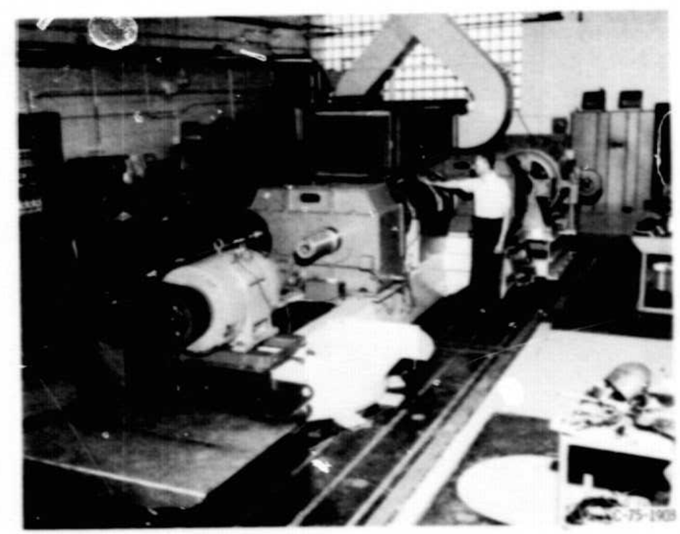


Figure 6. - 100 KW Wind turbine power train assembly under test.

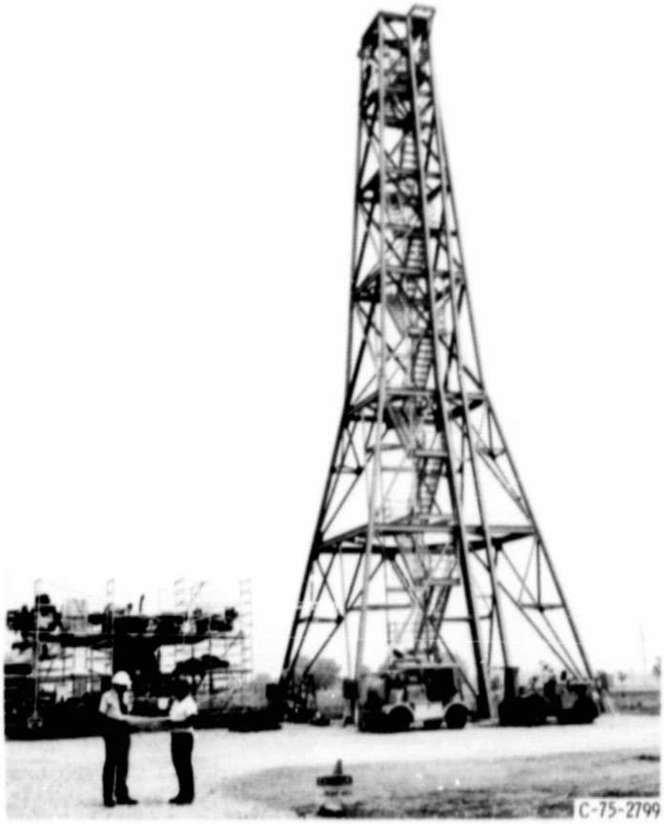


Figure 7. - 100 KW Wind turbine prior to final assembly at Plumbrook site.

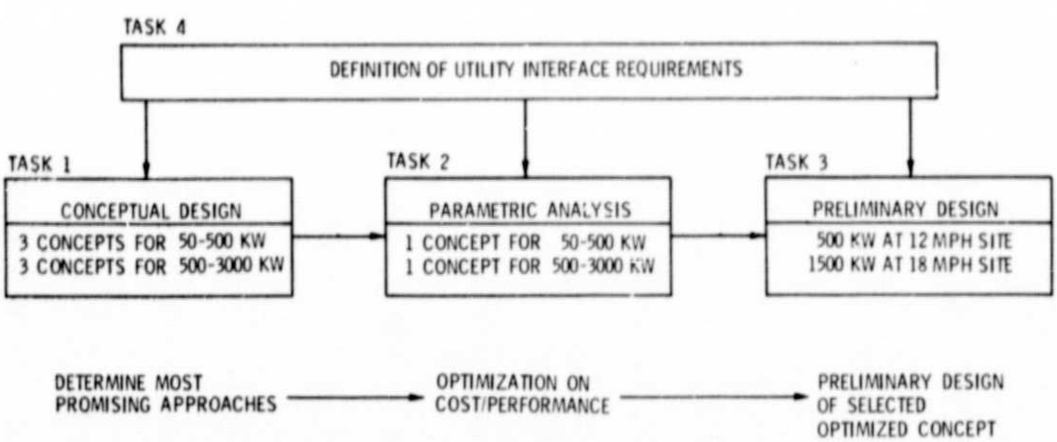


Figure 8. - Wind turbine design study tasks.

ROTOR	TRANSMISSION	GENERATORS
VARIABLE PITCH CONSTANT SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS
VARIABLE PITCH CONSTANT SPEED	TWO SPEED RATIO GEAR	AC SYNCHRONOUS
FIXED PITCH CONSTANT SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS
FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	DC GENERATOR MOTOR/GENERATOR
FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS TRANSFORMER & RECTIFIER MOTOR/GENERATOR
FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS TRANSFORMER & RECTIFIER SOLID STATE INVERTER
FIXED PITCH VARIABLE SPEED	VARIABLE RATIO	AC SYNCHRONOUS
FIXED PITCH CONSTANT SPEED VARIABLE DIAMETER	FIXED RATIO GEAR	AC SYNCHRONOUS

Figure 9. - Candidate wind turbine configurations evaluated during conceptual design task.

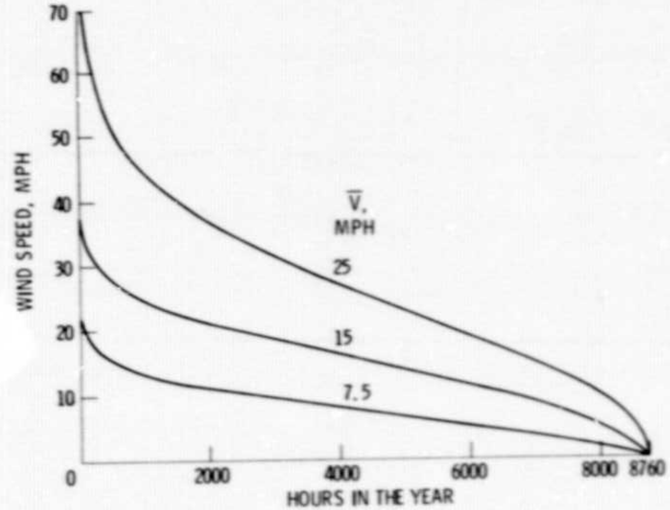


Figure 10. - NASA furnished wind velocity duration curves.

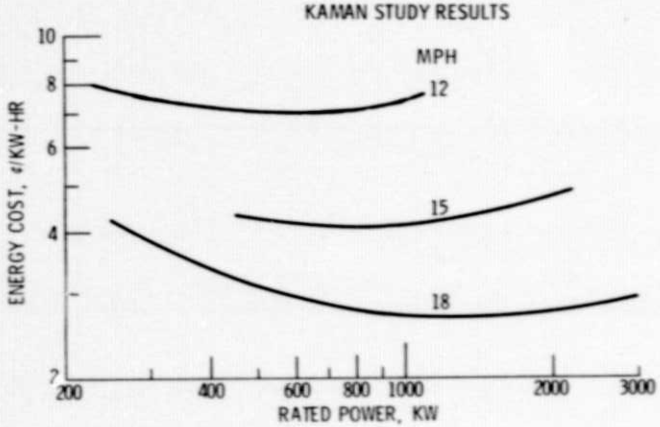


Figure 11(a). - Wind turbine energy cost as a function of mean wind speed and rated power.

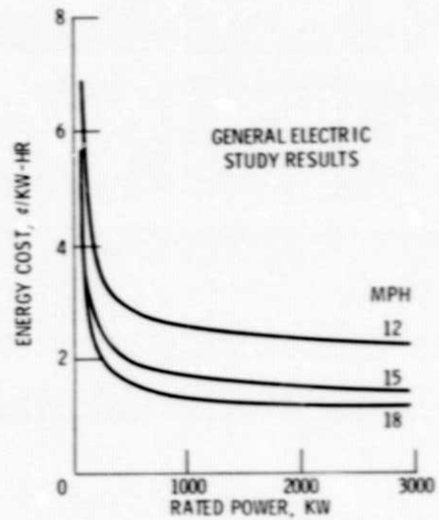


Figure 11(b). - Wind turbine energy cost as a function of mean wind speed and rated power.

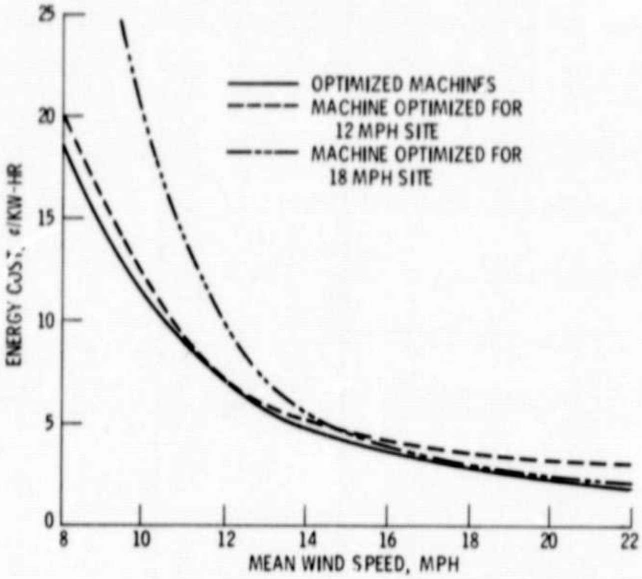


Figure 12. - Effect of siting-12 and 18 mph optimized machines located in various wind regimes

MANUAL DISCONNECTS MANDATORY
SINGLE BREAKER ON TRANSFORMER HIGH SIDE
UNIT CONNECTIONS TO DISTRIBUTION SYSTEM
LOCK OUT FOR INTERNAL FAULTS
RE-SYNC FOR EXTERNAL FAULTS - (STAND BY MODE)
  1 MINUTE DELAY - LOCK OUT AFTER 3 CYCLES
SEPARATE STATION SERVICE TRANSFORMER
EMERGENCY POWER - BATTERY 48 V
PF CAPACITORS - HIGH SIDE, SEPARATE BREAKER
REGULATION & STABILITY REQUIREMENTS DEPEND ON SITE
LIGHTNING SUPPRESSION AT GENERATOR & TRANSFORMER
DISTRIBUTION VOLTAGES FROM 2400 TO 34 500 V

Figure 13. - Wind turbine interface requirements for connection to a utility grid.

MAINTENANCE AND SAFETY
ENVIRONMENTAL IMPACT
LICENSING
APPLICATIONS

Figure 14. - Wind turbine operational and institutional issues.

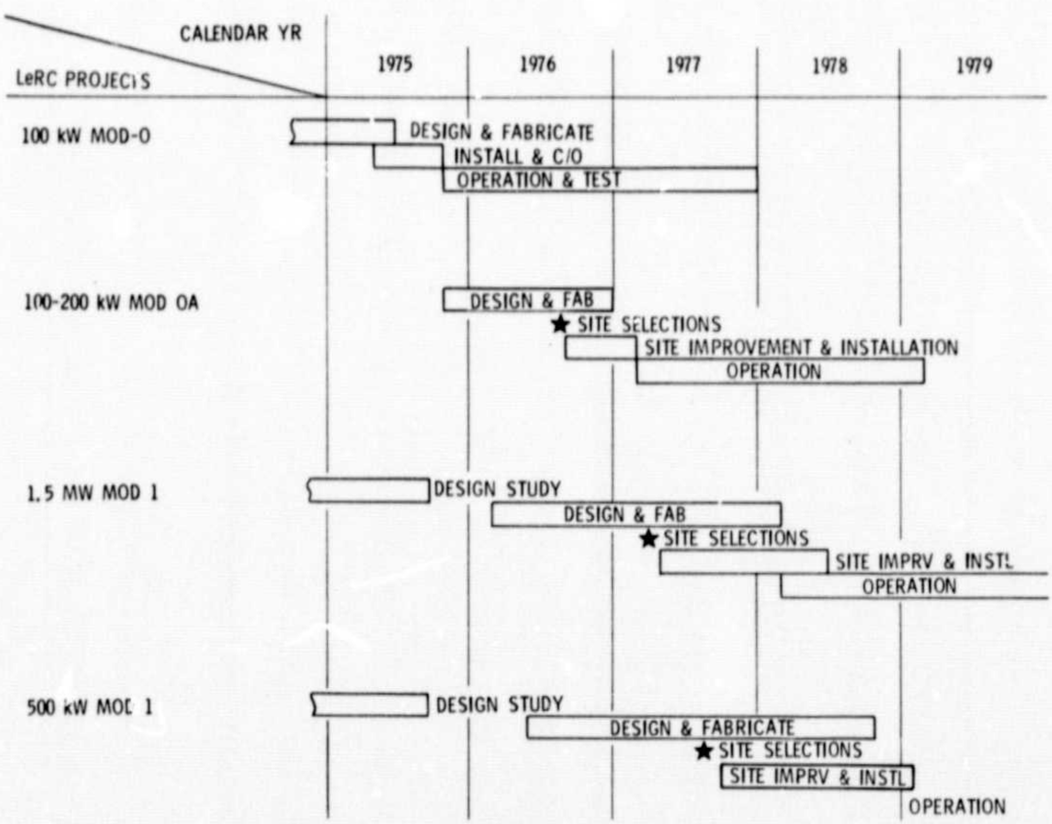


Figure 15. - Schedule for large experimental wind turbines.